

The Phantom of the OPERA: Superluminal Neutrinos*

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This report presents a brief review on the experimental measurements of the muon neutrino velocities from the OPERA, Fermilab and MINOS experiments and that of the (anti)-electron neutrino velocities from the supernova SN1987A, and consequently on the theoretical attempts to attribute the data as signals for superluminality of neutrinos. Different scenarios on how to understand and treat the background fields in the effective field theory frameworks are pointed out. Challenges on interpreting the OPERA result as a signal of neutrino superluminality are briefly reviewed and discussed. It is also pointed out that a covariant picture of Lorentz violation may avoid the refutation on the OPERA experiment.

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I. THE PHANTOM OF THE OPERA

The report that the OPERA Collaboration has unveiled evidence for a faster-than-light speed of muon neutrinos has caused a stir among physical society as well as public media. The light speed c is considered as the uppermost high speed of any kind of particles in special relativity, thus the OPERA experiment puts up a strong challenge to Einstein's theory of relativity. Since the release of the OPERA paper [1] on September 23 of 2011, there have been a fast growing number (over a hundred) of papers in the arXiv, discussing the the OPERA neutrino anomaly from various aspects. The OPERA anomaly of neutrinos is just like “the Phantom of the Opera” behind the mask, we are still unclear whether it is a ghost or something else at this stage.

OPERA stands for “the Oscillation Project with Emulsion-tRacking Apparatus”, which is an instrument for the investigation on neutrino oscillations. The experiment [1] is a collaboration between CERN in Geneva, Switzerland, and the Laboratori Nazionali del Gran Sasso (LNGS) in Gran Sasso, Italy. It exploits neutrinos from CERN to Gran Sasso (CNGS). The muon neutrinos in the CERN-CNGS neutrino beam were detected by the OPERA detector over a baseline of about 730 km. Compared to the time taken for neutrinos traveling at the speed of light in vacuum, an earlier arrival time of $(60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)})$ ns was measured. The neutrino velocity v is thus measured and its difference with respect to the vacuum light speed c is $(v - c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$ at a significance of 6σ .

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The OPERA result surprised people because of its magnitude of the superluminality of 10^{-5} , which is bigger compared to any previous constraints. Another reason is because of its high precision with big significance, which means that the conclusion should be reliable to an undoubtable confidence level if one can not find error in the experiment. In fact, there have been similar long baseline experiments of the same kind. The first direct measurement of neutrino velocity has been performed at Fermilab thirty years ago [2, 3]. Based on 9,800 events, measurements of the velocity of muon neutrinos with energy ranging from 30 GeV to 200 GeV gave $|\beta_\nu - 1| < 10^{-5}$, where $\beta_\nu \equiv v_\nu/c$. Just a few years ago, by using the NuMI neutrino beam, the MINOS Collaboration [4] analyzed a total of 473 far detector neutrino events with an average energy 3 GeV. They reported a shift with respect to the expected time of flight of $\delta_t = -126 \pm 32$ (stat) ± 64 (sys) ns, which corresponds to a constraint on the muon neutrino velocity, $(v_\nu - c)/c = (5.1 \pm 2.9) \times 10^{-5}$ at 68% confidence level. This 1.8σ signal was considered to be compatible with also zero, therefore it does not provide a strong evidence of Lorentz violation effects. However, with the new measurement of OPERA detector, it is surprising to notice that the Fermilab and MINOS results are compatible with the OPERA result, though at much lower statistics.

Besides the long baseline experiments, there are also measurable phenomenologies of superluminal neutrinos in astrophysics. For instance, supernova explosion (SNe) is an extremely luminous event, which causes a burst of radiation that outshines an entire galaxy. The radiation includes photons in a board range of spectrum, as well as neutrinos. Actually, most energy of a SNe is released in the form of neutrinos, however, due to the weak interactions of neutrinos with matters, only one event was observed with neutrino emissions on 23 February 1987, 7:35:35 UT (± 1 min) — the Supernova 1987A in the Large Magellanic Cloud [5, 6], which was optically observed on 24 February 1987. More than ten neutrinos were recorded with a directional coincidence within the location of supernova explosion, several hours before the optical lights were observed. Because of weak interactions, neutrinos leak out of the dense environment produced by the stellar collapse before the optical depth of photons becomes visible. Hence an early-arrival of neutrinos is expected. The journey of propagation of photons and neutrinos are of astrophysical distance (~ 51.4 kpc), hence it provides a unique opportunity to measure [7] the speed of neutrinos to be within the light speed with a precision of $\sim 2 \times 10^{-9}$.

Interestingly, while the OPERA results seem to be in remarkable consistence with other terrestrial muon neutrino velocity measurements, they contradict with the Supernova 1987A neutrino observation severely. The neutrinos detected from the Supernova are mainly anti-electron neutrinos with energy around 10 MeV, rather than 10 GeV scale muon neutrinos in the Fermilab, MINOS, and OPERA experiments. The electron neutrinos of SN1987a also put bound on the deviation of the velocity of neutrinos $v_{\bar{\nu}_e}$ with respect to the light speed c : $|(v_{\bar{\nu}_e} - c)/c| \leq 2 \times 10^{-9}$. The experimental data or bounds on the neutrino velocities are listed in Table I. As the observation of neutrinos from the Supernova is more reliable in time measurement, people also take this confliction as a severe challenge to the correctness of the OPERA experiment. It is expected that detection of neutrinos from future galactic supernova will be helpful not only for the study of neutrino velocities [8], but also for the investigation of other neutrino properties [9]. The detection of cosmogenic neutrino spectrum is also useful to learn about the Lorentz violation effects in the neutrino sector [10].

After the first release of the OPERA result, there have been many criticisms and doubts on the correctness of the experiment, such as whether the clocks at the two sides of CERN and LGNS are correctly adjusted by GPS technique as well as whether the distance between the two sides is properly measured, and whether the beam duration treatment of the data can introduce bias in the neutrino arrival time measurement. The OPERA collaboration

TABLE I: Data/bounds on neutrino velocities from OPERA, Fermilab, MINOS, and SN 1987A data

OPERA	Energy (GeV)	13.9	42.9						
	$\frac{v_{\nu\mu}-c}{c} \text{ (10}^{-5}\text{)}$	2.17 ± 0.83	2.74 ± 0.80						
Fermilab	Energy (GeV)	32	44	59	69	90	120	170	195
	$\frac{v_{\nu\mu}-c}{c} \text{ (10}^{-5}\text{)}$	-2^{+2}_{-3}	2 ± 7	-1^{+2}_{-3}	-1^{+2}_{-3}	1^{+3}_{-4}	1 ± 7	1^{+2}_{-3}	6^{+3}_{-4}
MINOS	Energy (GeV)	3							
	$\frac{v_{\nu\mu}-c}{c} \text{ (10}^{-5}\text{)}$	5.1 ± 2.9							
SN1987A	Energy (MeV)	~ 10							
	$\frac{v_{\nu e}-c}{c} \text{ (10}^{-9}\text{)}$	≤ 2							

repeated [11] the measurement over the same baseline without any assumptions about the details of neutrino production during the spill, such as energy distribution or production rate, by using a new CERN beam which provided proton pulses of 3 nanoseconds each with 524 nanosecond gaps. Without using the earlier statistical computation, the OPERA collaboration measured twenty events indicating neutrinos had traveled faster than light by 60 ns, with 10 ns uncertainty. The error bounds for the original superluminal speed fraction were tightened further to $(2.37 \pm 0.32(\text{stat.}) + 0.34/-0.24(\text{sys.}))10^{-5}$, with the new significance level becoming 6.2σ .

The neutrino speed anomaly of the OPERA is now a “phantom”. The re-confirmation of the OPERA result reminds us that the game just begins, it is far from the end. Whether we believe it or not, the phantom of the OPERA is there, deep down below the earth with a mask. We need to finger it out, whether it is a ghost or an angel of music.

II. THE OPERA PHANTOM AS A SIGNAL FOR LORENTZ VIOLATION

Nowadays, there has been an increasing interest in Lorentz invariance Violation (LV or LIV) both theoretically and experimentally [12]. Special relativity, or Lorentz symmetry, is one of the foundations of modern physics and has been proved to be valid at very high precision. However, the possible Lorentz symmetry violation (LV) effects are sought for decades from various theories, motivated by the unknown underlying theory of quantum gravity together with various phenomenological applications [13–18]. This can happen in many alternative theories, e.g., the doubly special relativity (DSR) [19–21], torsion in general relativity [22–24], non-covariant field theories [25–28], and large extra-dimensions [29, 30]. From basic consideration, there were investigations on the concepts of space-time such as whether the space-time is discrete or continues [31–33], or whether a fundamental length scale should be introduced to replace the Newtonian constant G [34]. It has been revealed from physical arguments that space-time is discrete rather than continuous [33], and we also know that the introduction of the minimal length scale can be manifested through the Lorentz violation [34]. The existence of an “aether” or “vacuum” can also bring the breaking down of Lorentz invariance [35, 36].

Although the OPERA result has been largely debated, neutrino velocity anomaly appears to be a strong challenge to the well-known fact in special relativity that no physical particle travels faster than the light. One of the fundamental principles of relativity is the Lorentz invariance, which states that the equations describing the laws of physics have the same form in all admissible frames of reference. Therefore it seems a natural attempt to attribute the OPERA anomaly as a signal for Lorentz invariance violation. The first a few papers [37, 38] on the OPERA anomaly are phenomenological analysis to use some kind of modified dispersion relations to fit the data. Consequently there

are a number of papers [39–49] to seek for the possibilities for superluminal neutrinos from Lorentz violation in various theoretical models. In fact, the possibilities of superluminal neutrinos were proposed with an earlier version of standard model extension (SME) [50] and with extra-dimensions [29, 30] before the OPERA experiment. There were also attempts [51–54] to reproduce the neutrino oscillations through Lorentz violation rather than from mass difference as in the conventional treatment [55].

Here I focus on the attempts [39–41] to attribute the OPERA anomaly as a signal of Lorentz violation in the effective field theory frameworks based on traditional techniques in particle physics. A useful model on Lorentz violation is the minimal Standard Model Extension (SME), in which Lorentz violation terms are constructed with standard model fields and controlling coefficients are added to the usual standard model (SM) Lagrangian [56]. The origins for such LV operators are suggested in many ways, of which spontaneous Lorentz symmetry breaking proposed first in string theory is widely recognized [57]. The minimal SME is first applied in Ref. [40] to confront with the OPERA result as an indication for superluminal neutrinos. There is also a recent proposal to derive some supplementary LV terms from standard model with a basic principle of the physical invariance with respect to the mathematical background manifolds [58, 59], and such a standard model supplement (SMS) framework has been applied to discuss the Lorentz violation effects for the cases of Dirac particles [58], photons [59–61], and neutrinos [39], in which the superluminal neutrinos as a signal of Lorentz violation was suggested. Here we do not go into theoretical details, but outline the basic concepts why the effective Lagrangians of effective field theory frameworks can bring the superluminality of neutrinos and how one can handle the Lorentz violation effects in such frameworks.

The general effective field theory framework starts from the Lagrangian of the standard model, and then includes additional terms containing the Lorentz violation effects. The magnitudes of these LV terms can be constrained by various experiments. The Coleman-Glashow model [62] is a most simple version of the effective field theory framework with a scalar constant as the LV parameter. In the minimal version of the SME [56], the LV terms are measured with several tensor fields as coupling constants, and modern experiments have built severe constraints on the relevant Lorentz violation parameters [13]. In the SMS framework [58, 59], the LV terms are brought about from a basic principle denoted as the physical independence (or physical invariance), which requires that the equations describing the laws of physics have the same form in all admissible mathematical manifolds. Such principle leads to the introduction of some Lorentz violation matrices $\Delta^{\alpha\beta}$ to the standard model particles under consideration, with the elements of these LV matrices to be measured or constrained from experimental observations rather than from theory at first. Therefore one may also consider the LV matrices in the SMS framework as similar to the background tensor fields in the minimal SME model.

The Coleman-Glashow model [62] is a simple version to include Lorentz violating terms into the standard model Lagrangian. Let Ψ denote a set of n complex scalar fields assembled into a column vector. With the invariance under the $U(1)$ group $\Psi \rightarrow e^{-i\lambda}\Psi$, the most general free Lagrangian is: $\mathcal{L} = \partial_\mu \Psi^* Z \partial^\mu \Psi - \Psi^* M^2 \Psi$, where Z and M^2 are positive Hermitian matrices. One can always linearly transform the fields to make Z the identity and M^2 diagonal, thus obtaining the standard theory of n decoupled free fields. One can then add to the standard model Lagrangian the Lorentz-violating term:

$$\mathcal{L} \rightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi, \quad (1)$$

where ϵ is a Hermitian matrix that signals the Lorentz violation in the Coleman-Glashow model.

The SME Lagrangian in the neutrino sector takes the form [40, 52, 56]

$$\mathcal{L} = \frac{1}{2} i \bar{\nu}_A \gamma^\mu \overleftrightarrow{D}_\mu \nu_B \delta_{AB} + \frac{1}{2} i c_{AB}^{\mu\nu} \bar{\nu}_A \gamma^\mu \overleftrightarrow{D}_\nu \nu_B - a_{AB}^\mu \bar{\nu}_A \gamma^\mu \nu_B + \dots, \quad (2)$$

where $c_{AB}^{\mu\nu}$ and a_{AB}^μ are Lorentz violation coefficients resulting from tensor vacuum expectation values in the underlying theory, the subscripts A, B are flavor indices, and the ellipsis denotes the non-renormalizable operators (eliminated in the minimal SME). The first term in Eq. (2) is exactly the SM operator, and the second and third terms (CPT-even and CPT-odd respectively) describe the contribution from Lorentz violation.

For the electroweak interaction sector, the Lagrangian of fermions in the SMS framework can be written as [39, 58, 59]

$$\begin{aligned} \mathcal{L}_F = & i \bar{\psi}_{A,L} \gamma^\alpha \partial_\alpha \psi_{B,L} \delta_{AB} + i \Delta_{L,AB}^{\alpha\beta} \bar{\psi}_{A,L} \gamma_\alpha \partial_\beta \psi_{B,L} \\ & + i \bar{\psi}_{A,R} \gamma^\alpha \partial_\alpha \psi_{B,R} \delta_{AB} + i \Delta_{R,AB}^{\alpha\beta} \bar{\psi}_{A,R} \gamma_\alpha \partial_\beta \psi_{B,R}, \end{aligned} \quad (3)$$

where A, B are flavor indices. The Lorentz violation terms are uniquely and consistently determined from the standard model by including the Lorentz violation matrices $\Delta^{\alpha\beta}$, which are generally particle-dependent [59] with flavor indices. For leptons, $\psi_{A,L}$ is a weak isodoublet, and $\psi_{A,R}$ is a weak isosinglet. After the calculation of the doublets and classification of the Lagrangian terms again, the Lagrangian can be written in a form like that of Eq. (3) too. Assume that the Lorentz violation matrix $\Delta_{AB}^{\alpha\beta}$ is the same for the left-handedness and right-handedness, namely $\Delta_{L,AB}^{\alpha\beta} = \Delta_{R,AB}^{\alpha\beta} = \Delta_{AB}^{\alpha\beta}$. Without considering mixing between flavors, one can rewrite Eq. (3) as

$$\mathcal{L}_F = \bar{\psi}_A (i \gamma^\alpha \partial_\alpha - m_A) \psi_A + i \Delta_{AA}^{\alpha\beta} \bar{\psi}_A \gamma_\alpha \partial_\beta \psi_A, \quad (4)$$

where $\psi_A = \psi_{A,L} + \psi_{A,R}$, i.e., the field ψ_A is the total effects of left-handed and right-handed fermions of the given flavor A . When there is only one handedness for fermions, ψ_A is just the contributions of this one handedness, which is the situation for neutrinos. The mass term in the Lagrangian \mathcal{L}_F is included, one can let $m_A \rightarrow 0$ for massless fermions.

However, as the LV terms in the general effective field theory frameworks can be considered as added by hands rather than from basic theories, there exist different scenarios on how to understand these background fields and also on how to handle them. We list three options of possible understandings and treatments:

- **Scenario I:** which can be called as fixed background scenario in which the backgrounds are taken as fixed parameters in any inertial frame of reference the observer is working. It means that the backgrounds can be taken as with the same formalism and with approximately the same parameters for any working reference frames such as earth-rest frame, sun-rest frame, or CMB frame for an observer. This scenario can be adopted when the observer is focusing on the Lorentz violation effect within a certain frame and does not care about relations between different frames, or the situation could become very complicated with different formalisms in different frames from the requirement of consistency. This scenario can apply as a practical tool for all of the above mentioned three versions of the effective field theory framework: the Coleman-Glashow model, the minimal SME, and the SMS framework.
- **Scenario II:** which can be called as “new æther” scenario in which the background fields transform as tensors between different inertial frames of reference but keep unchanged within the same frame. It means that there exists a privileged inertial frame of reference in which the background can be considered as the “new æther”,

i.e., the “vacuum” at rest, which changes from one frame to another frame by Lorentz transformation. Within a same frame of reference, these background fields are just treated as fixed parameters. This scenario cannot apply directly to the Coleman-Glashow model, as in this model the LV parameter is a scalar which should keep invariant in any working reference frames, but it can apply to the minimal SME and also to the SMS. In fact, the previous phenomenological analysis in the minimal SME are based on this scenario.

- **Scenario III:** which can be called as covariant scenario in which the background fields transform as tensors adhered with the corresponding standard model particles. It means that these background fields are emergent and covariant with their standard model particles. This scenario cannot apply to the Coleman-Glashow model, but can apply to the minimal SME and also to the SMS. Such a scenario probably still has not been considered in previous studies in the effective field theory with normal Lorentz transformation.

Now we come to the question how the Lorentz violation effects can exist in the different scenarios of Lorentz violation in the effective field theory framework. Generally, the mass energy relation of particles with 4-momentum p_μ and mass m can become

$$p^2 = m^2 + \lambda(\Delta_1, \dots, \Delta_j, \dots, \Delta_n, p), \quad 1 \leq j \leq n \quad (5)$$

where the parameters/tensors Δ_j represent background fields which influence the corresponding standard model particles and λ is a new quantity that signals the Lorentz invariance violation. Different frameworks of Lorentz violation have different parameters Δ_j . Within the standard model, we cannot observe these background fields. So we just focus on the particles of the standard model, make Lorentz transformations on these particles, and then find that all equations are Lorentz invariant. But when we add terms including Δ_j coupling with these particles and still make Lorentz transformation on just these same particles, the equations with the added terms are found to violate Lorentz invariance this time. So in this sense, the added terms violate Lorentz invariance. Thus Δ_j are the tensors violating Lorentz invariance. On the other hand, when the background tensors Δ_j are Lorentz covariant with these particles too, the equations are still Lorentz invariant, because all the space-time indices in the added terms are contracted generally. That is to say, when both p and Δ_j of Eq. (5) are Lorentz transformed to $\hat{R}(p)$ and $\hat{R}(\Delta_j)$ respectively, Eq. (5) is still Lorentz invariant. So the Lorentz violation frameworks (e.g. the SMS and the SME) violate the common Lorentz invariance of the standard model, but keep the Lorentz invariance in the new sense that the background Lorentz violation tensors are Lorentz covariant too. With the terminology for Lorentz violation theories, we say that the Lorentz violation frameworks break the Lorentz invariance but keep the Lorentz covariance. It is also possible that the added terms break both the Lorentz invariance and the Lorentz covariance, such as the situation of the Coleman-Glashow model, but in this case the introduction of different formalisms between different reference frames can not be avoided for consistency and this makes things very complicated. In all of the above three scenarios of Lorentz violation, the motions of these standard model particles are influenced by the background fields, therefore the Lorentz violation effects do exist as compared with the situation without background fields. Then the energy-momentum dispersion relation of a particle is different from that in the free case. One thus can calculate the particle velocity through the new dispersion relation, in which the background fields enter as parameters. The velocity of a particle could be therefore superluminal or subluminal by adjusting the LV parameters. By confronting with the OPERA result, the LV parameters are estimated in Ref. [39] for the SMS framework and in Ref. [40] for the minimal SME.

As there are a large number of parameters in the minimal SME and the SMS framework, there are still large degrees of freedom to fit the OPERA, Fermilab, MINOS and supernova data for superluminal neutrinos. Therefore it is still too early to suggest a specific model at the moment but we refer to Refs. [39, 40] for some possible choices of simple toy models to confront with data. However, we noticed that to reconcile the difference between the muon neutrino data of OPERA, Fermilab and MINOS and the electron neutrino data of supernova, we may investigate along two possible directions:

- The flavor dependence: the observation that the species of supernova neutrinos are different from those of terrestrial neutrinos — the former being electron (and/or anti-electron) neutrinos, while the measured collider neutrinos from OPERA are muon neutrinos. We suspect a family hierarchy should be responsible for the observed different velocities [39, 63]. In the dispersion relations, Lorentz violation coefficients of different flavors are generally different, hence if there exist family hierarchies of these parameters, the different propagation behaviors of supernova neutrinos and terrestrial muon neutrinos can be understood.
- The energy dependence: the observation that the supernova electron neutrinos are of 10 MeV scale while the collider muon neutrinos are of 10 GeV scale may lead to possible energy dependence in the dispersion relation to reconcile with the different superluminalities for collider neutrinos and supernova neutrinos. There have been a number of models [47, 64] can realize such a requirement phenomenologically.

There are also other ideas on the different neutrino velocities between OPERA and supernova, such as by including the matter effect in the earth crust [65] and by the introduction of sterile neutrinos which may take a shortcut in propagation [66–68].

III. A CHALLENGE ON THE RATIONALITY OF THE OPERA RESULT

Cohen and Glashow argued [69] that if the Lorentz violation of the OPERA experiment is of 10^{-5} , the high energy muon neutrinos exceeding tens of GeVs can not be detected by the Gran Sasso detector, mainly because of the energy-losing process $\nu_\mu \rightarrow \nu_\mu + e^+ + e^-$ analogous to Cherenkov radiations through the long baseline about 730 km. Bi *et al.* also argued that the Lorentz violation of muon neutrinos of order 10^{-5} will forbid kinematically the production process of muon neutrinos $\pi \rightarrow \mu + \nu_\mu$ for muon neutrinos with energy larger than about 5 GeV [70]. Such arguments put up a strong challenge to the rationality of the OPERA experiment and the consequent suggestion to attribute the OPERA experiment as a signal of Lorentz violation.

As we have pointed out, the Cohen-Glashow argument is based on the Coleman-Glashow model [62] of Lorentz violation, and their argument is based on some implicit assumptions, such as that the Lorentz violation is measured by just a scalar Lorentz violation parameter. Such a conclusion is not valid in general in other Lorentz invariance violation frameworks. A response to Cohen, Glashow is offered in Ref. [71], where Amelino-Camelia, Freidel, Kowalski-Glikman and Smolin argued that the energy threshold for the anomalously Cherenkov analogous process $\nu_\mu \rightarrow \nu_\mu + e^+ + e^-$ makes physical event observer-dependent. They pointed out that the deformed Lorentz transformation can avoid the problem brought about by these arguments. There have been a number of investigations [72–75], indicating that these analogous Cherenkov radiations can be avoided by adopting some forms of deformed Lorentz transformations. The frameworks with deformed Lorentz transformation, such as the doubly special relativity [19–21], might be cataloged into the covariant picture of Lorentz violation.

It is also pointed in Ref. [41] that the Cohen-Glashow argument is not valid in general in other Lorentz invariance violation frameworks in which the Lorentz invariance is breaking whereas the Lorentz covariance still holds, such as the standard model supplement (SMS) [58, 59] or the standard model extension (SME) [56]. The derived dispersion relations in the minimal SME and the SMS might be treated with an option as covariant with the momentum of the muon neutrino and thus can avoid the Cherenkov-like radiations.

It has been reported [76] by the ICARUS Collaboration that there is no evidence for the analogues Cherenkov radiation of muon neutrinos from CERN to the LNGS, where the OPERA experiment is also performed. If taking the arguments of Cohen-Glashow and Bi *et al.* as true, then one must refute the OPERA result of neutrino superluminality as Ref. [76] did. However, we take the ICARUS result as a support of our argument on the forbidding of these Cherenkov-like processes, rather than a refutation of the OPERA result. Therefore our argument can accommodate both the OPERA and the ICARUS experiments, whereas one must refute the OPERA result of superluminality or the ICARUS result of no analogues Cherenkov radiation based on the arguments for these Cherenkov-like processes. It is not adequate to refute an experimental observation by just pure theoretical argument, but instead, reliable experimental observations can be used to rule out theoretical arguments. From a phenomenological viewpoint, what reported by the ICARUS Collaboration of no Cherenkov-like radiation is just among one part of the observation by the OPERA Collaboration already. What they did is just to rely on a theoretical argument to refute the superluminality part of the OPERA result.

The covariant picture of Lorentz violation, whether in the effective field theory or in some kind of frameworks with deformed Lorentz transformation, might accommodate the superluminality of neutrinos with no Cherenkov like radiation. This might provide a possible way for a consistent approach to handle the Lorentz violation effects.

IV. CONCLUSION

Researches on Lorentz violation have been active for many years, with various theories have been proposed and many phenomenological studies have been performed to confront with various observations. Though there have been many phenomena which could be marginally considered as possible evidences or hints for Lorentz violation, there is no convincing evidence yet, including the OPERA anomaly, which is still a phantom under a mask. There are still many challenges to attribute the OPERA anomaly as an evidence for Lorentz violation, however, the OPERA anomaly provides a new chance for Lorentz violation study. The re-confirmation of the experiment by the OPERA collaboration itself reminds us that “the phantom of the OPERA” just begins, and we still need some stages to reveal the true face of this OPERA phantom. We conclude that Lorentz violation is becoming an active frontier to explore both theoretically and experimentally.

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